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Mars Phobos and Deimos Survey (M-PADS)—A Martian Moons Orbiter and Phobos Lander

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Abstract

We describe a Mars ‘Micro Mission’ for detailed study of the martian satellites Phobos and Deimos. The mission involves two ~330 kg spacecraft equipped with solar electric propulsion to reach Mars orbit. The two spacecraft are stacked for launch: an orbiter for remote investigation of the moons and in situ studies of their environment in Mars orbit, and another carrying a lander for in situ measurements on the surface of Phobos (or alternatively Deimos). Phobos and Deimos remain only partially studied, and Deimos less well than Phobos. Mars has almost always been the primary mission objective, while the more dedicated *Phobos* project (1988-89) failed to realise its full potential. Many questions remain concerning the moons’ origins, evolution, physical nature and composition. Current missions, such as *Mars Express*, are extending our knowledge of Phobos in some areas but largely neglect Deimos. The objectives of M-PADS focus on: origins and evolution, interactions with Mars, volatiles and interiors, surface features, and differences. The consequent measurement requirements imply both landed and remote sensing payloads. M-PADS is expected to accommodate a 60 kg orbital payload and a 16 kg lander payload. M-PADS resulted from a BNSC-funded study carried out in 2003 to define candidate Mars Micro Mission concepts for ESA’s Aurora programme.

1 Introduction

This paper results from mission study work completed during 2003 for the British National Space Centre (BNSC) by the industrial company QinetiQ and academic partners at the Open University’s Planetary and Space Sciences Research Institute. The aim was to study possible missions to fulfil the objectives of the ‘Mars Micro Mission’, an Arrow-class mission as outlined in ESA’s Aurora programme. The stated aims of the Mars Micro Mission were to “demonstrate advanced electric propulsion and miniaturised avionics”¹. No overall mission objective had been defined, but it was assumed that the mission must also be relatively low cost (e.g. cheaper than *Mars Express*) yet perform highly relevant science once at Mars. In addition, it was assumed that technology readiness must be appropriate to a Phase A study no later than 2007.

Three concepts emerged from a workshop held to discuss possible science goals and mission configurations. The other two concepts address the martian atmosphere and martian sub-surface ice (Walker et al., 2003, 2006), while the concept developed here focuses on the martian moons Phobos and Deimos. Two mini-satellites, launched as a pair, would perform remote measurements at both moons and in situ measurements at the surface of one of them. In the following sections, we describe the scientific context and goals of such a mission, the spacecraft and their journey to Mars, the scientific payload they would carry, and the operational scenario in the martian system.

2 Scientific Background

Phobos and Deimos were discovered in 1877. Phobos orbits Mars in less than a martian day (‘subsynchronous’); the resulting tidal effects mean Phobos is slowly spiralling in towards Mars. The ultimate outcome is a matter of debate—Phobos may break up and form a ring of debris, it may collide with

¹ ESA Aurora Briefing: “Near Term Missions Planning”, 4th Exploration Programme Advisory Committee meeting, 17/07/2002

Mars, or resonances may eject it from Mars orbit. In contrast, Deimos is in a supersynchronous orbit and the same tidal effects cause it to retreat from Mars. Both moons are tidally locked into synchronous rotation, always presenting the same face towards Mars, albeit with small librations about this point.

Both are irregularly-shaped, ‘asteroid-like’ worlds, and in fact may have originated as primitive asteroids (or as fragments of a single, tidally-disrupted parent asteroid), that early in Mars’ history were captured into martian orbit. The best-fit triaxial ellipsoids have axes of $26.1 \times 22.2 \times 18.6$ and $15.6 \times 12.0 \times 10.2$ km³ for Phobos and Deimos, respectively (Stooke, 1998, after Thomas and Simonelli). Their bulk densities are 1530 ± 100 and 1340 ± 828 kgm⁻³, respectively (Smith et al., 1995). Their surfaces exhibit craters and regolith, however Deimos is much smoother and less cratered. Phobos has a large, ~10 km diameter crater named Stickney, and a system of linear grooves attributed to the impact of ejecta thrown up from large impacts on Mars, less of which manages to reach Deimos (Murray et al., 1994, 2006). However, many workers still attribute these grooves to the surface expression of internal features (fractures from large impacts or layering of a differentiated parent body) and point to other systems of grooves found on asteroids such as Gaspra, Ida and Eros (e.g. Horváth et al., 2001; Asphaug et al., 2002). In terms of reflectance spectrometry of their surfaces, Phobos exhibits two distinct spectral units, a ‘redder’ unit and a ‘bluer’ unit, the latter associated with the walls and ejecta of Stickney. T-type asteroids and highly space-weathered mafic mineral assemblages are the closest spectral matches to parts of the surface (Murchie and Erard, 1996; Rivkin et al., 2002). Deimos resembles a D-type asteroid. More recently, it has been suggested that the Kaidun meteorite originates from Phobos (Ivanov, 2004).

Phobos and Deimos produce measurable effects in the vicinity of their orbits. In addition to the debated possibility of Phobos (at least) possessing an intrinsic magnetic field (e.g. Veselovsky, 2004), neutral gas tori are formed around Mars by material from the moons, and the local plasma environment and solar wind are disturbed (e.g. Baumgartel et al., 1996, 1998; Yeroshenko, 2000, Mordovskaya et al., 2001). Models of the production of ejecta from impacts onto the moons and data from *Phobos 2* suggest the existence of dust discs / halos (e.g. Ishimoto, 1996; Ishimoto et al., 1997; Krivov and Hamilton, 1997; Krivov and Jurewicz, 1999), though they have not yet been positively detected by observations (Krivov et al., 2006; Showalter et al., 2006). The possibility of frozen volatiles such as water ice in the interior of Phobos (at least) is a matter for further investigation—there is evidence for outgassing of water molecules from the surface, and recent reanalysis of the *Phobos 2* ISM data provides tentative detection of hydrated minerals in small areas of the surface (Gendrin et al., 2005). The question of water ice inside Phobos was addressed by Fanale and Salvail (1990).

2.1 Exploration by Spacecraft

Table 1 summarises the past and forthcoming missions performing measurements of Phobos and/or Deimos. No observations of the moons are currently planned for the primary mission of *Mars Odyssey* (launched in 2001). Also excluded are lost spacecraft such as *Phobos 1*, the *Phobos 1* and 2 landers (DAS and PROP-F), *Mars Observer*, *Mars 96*, *Nozomi* (imaging of the moons was planned), *Mars Climate Orbiter* and *Beagle 2* (which had planned to observe Phobos and Deimos through geological filters). Several experiments on board *Mars Express* (MEx) have however been making occasional investigations of Phobos since May 2004, while Russia is planning to launch a Phobos sample return mission in 2011 (Zakharov, 2002; Marov et al., 2004). In addition there have been many Earth-based telescopic observations (e.g. Rivkin et al., 2002) including HST/WFPC2 (Cantor et al., 1999; Showalter et al., 2006) and radar (Ostro et al., 1989; Busch et al., 2007).

Table 1. Summary of past, current and forthcoming observations of Phobos and Deimos by space missions, including references in the case of the more recent missions.

Mission(s)	Year of Launch	Investigations performed
<i>Mariner 7</i>	1969	Distant imaging of Phobos
<i>Mariner 9</i>	1971	Imaging & UV spectrometry of Phobos & Deimos; radio science
<i>Mars 5</i>	1973	Measurements of the interaction of Deimos with the solar wind
<i>Viking Orbiters 1&2</i>	1975	Imaging & IR observations of Phobos & Deimos; radio science
<i>Viking Landers 1&2</i>	1975	Observations by lander cameras
<i>Phobos 2</i>	1988	Visible & near-IR imaging of Phobos by VSK-FREGAT (Avanesov et al., 1994); UV-Visible spectrometry by KRFM (Ksanfomality & Moroz, 1995); near-IR imaging spectrometry by ISM (Murchie & Erard, 1996; Gendrin et al., 2005); plasma & magnetic field measurements. The scientific objectives and experimental methods of the <i>Phobos</i> project were described by Sagdeev et al. (1988). More detailed discussion of the science and many of the experiments can be found in: <i>Phobos - Scientific and Methodological Aspects of the Phobos Study</i> (1988). Initial analysis of data from <i>Phobos 2</i> was published in groups of papers in each of the following journal issues: <i>Nature</i> 341 (6423), 1989; <i>Soviet Astronomy Letters</i> 16 (2), 1990, and <i>Planet. Space Sci.</i> 39 (1/2), 1991.
<i>Mars Pathfinder (MPF)</i>	1996	Observations of Phobos & Deimos by the IMP lander camera (Thomas et al., 1999; Murchie et al., 1999)
<i>Mars Global Surveyor (MGS)</i>	1996	MOC imagery of Phobos (Thomas et al., 2000); low-res thermal IR coverage by TES (Roush and Hogan, 2000); ranging by MOLA (≥ 265 km range) (Banerdt and Neumann, 1999); more observations were carried out during 2003.
<i>Mars Express (MEx)</i>	2003	HRSC is providing astrometric data on the two moons, and the first high-resolution global map of Phobos (Oberst et al., 2005), including the leading hemisphere previously covered only at low resolution (distant imaging of Deimos is also planned); OMEGA will complete the near-IR mineralogical mapping begun by its ‘ancestor’, ISM on <i>Phobos 2</i> ; PFS will also make observations, over a wider wavelength range in the IR than OMEGA; ASPERA-3 may measure sputtering from Phobos’ surface; MARSIS will examine the sub-surface with penetrating radar; SPICAM will also obtain UV and near-IR spectra.
<i>Mars Exploration Rovers (MER) (Spirit and Opportunity)</i>	2003	Phobos & Deimos solar transit observations
<i>Mars Reconnaissance Orbiter (MRO)</i>	2005	Observations of both moons by HiRISE and CRISM instruments
<i>Phobos-Grunt</i>	2011	Planned Phobos sample return

2.2 Current status and Near-Term Prospects

While many measurements of the moons have been made, many questions still remain concerning their origin, evolution, physical nature and composition. Phobos has received much better coverage than has Deimos, which has not been investigated at close quarters since *Viking*. Investigations have been patchy due to a mixture of mission failures and the fact that the study of the martian moons is usually an objective secondary to the study of Mars itself. Investigation of the origin and evolution of the martian system would be incomplete without detailed study of the moons in their own right and in their context as small bodies orbiting Mars. They are the only other satellites of a terrestrial planet beyond Earth's own Moon, and relative to the near-Earth asteroid population they are large, long-term residents of the inner Solar System. The best illustration of the unfinished exploration of the martian moons is the partial coverage of the surface of Phobos in the near-IR achieved by the ISM instrument on *Phobos 2*. Although covering only a fraction of the surface, the dataset provides a tantalising glimpse of the diversity in composition (e.g. Gendrin et al., 2005). The resolution of the visible mapping coverage of the moons varies greatly. Although one 5×15 km strip was imaged by *Mars Global Surveyor* at 2.43 m/pixel, large areas on the leading side were covered at around only 100 m resolution until *Mars Express* began observations.

Mars Express (MEx) is due to pass within 3000 km of Phobos many times during its mission lifetime—the observations under way mean that any subsequent mission such as that considered here will have to exceed or complement the results from MEx. Although very impressive, MEx will not of course be making in situ measurements on the surfaces of the moons, and will have much less opportunity to study Deimos in such detail. Also absent from MEx are instruments to measure more directly the moons' elemental compositions (the sputtering method is not the most effective way of doing this), perform thermal imaging, dust measurements, magnetometry and other plasma measurements, and detailed mapping of the moons' gravity fields.

In recent years, proposals for future missions to Phobos and / or Deimos have included:

- A 'low-cost' US-Russian Phobos-Deimos mission (Rahe et al., 1999; Mukhin et al., 2000; Karavasilis et al., 2003).
- The *Aladdin* Discovery mission proposal for Phobos and Deimos sample return (Pieters et al., 2000; Mueller et al., 2003).
- The *Gulliver* Deimos sample return Discovery mission proposal (Britt et al., 2003).
- *Phobos-Grunt* ('Phobos-Soil') sample return (Zakharov, 2002; Marov et al., 2004). An 'engineering model' of the surface of Phobos has been generated in support of this mission (Kuzmin et al., 2003; Kuzmin and Zabuleva, 2003).
- An ESA Technology Reference Study for Deimos sample return (Renton et al., 2004).
- A 30 kg Phobos lander was studied by NPO Lavochkin in 2001 for the CNES *Mars Premier* mission.
- Canadian Phobos mission studies PARTI (2002) and PRIME.
- Five Phobos/Deimos missions proposed to ESA's Aurora programme as a Mars Sample Return Precursor mission.

Although some of these proposals may eventually be realised, the uncertainties involved (at the time this study was performed) meant that it was prudent for the study to assume that none would happen prior to M-PADS.

2.3 M-PADS Objectives and Measurements

The philosophy for this study was to define a mission that would complete a comprehensive survey of Phobos and bring the coverage of Deimos up to a similar level. Based on a survey of the current state of knowledge of the martian moons in the published literature and a prioritised assessment of the outstanding scientific questions, the scientific objectives of a Mars Phobos and Deimos Survey (M-PADS) mission were defined as follows:

- Distinguish between different models of the origin of Phobos and Deimos (how, when, etc.)
- Establish (or disprove) a link between the moons and known types of asteroid (and, indeed, meteorite)

- How have Phobos and Deimos been affected by their association with Mars? How have Mars and its environment been affected by the presence of satellites?
- Do their interiors contain frozen volatiles such as water ice?
- Are the grooves on Phobos the result of collision with ejecta from impacts on Mars or the surface expression of internal features, e.g. impact-induced cracks?
- How and why do Phobos and Deimos differ, e.g. in surface morphology and composition?
- How do surface and sub-surface properties differ?

To address these questions requires the following for each moon. Note that the investigation of Deimos would resume from a lower baseline than that of Phobos. Those that are being addressed for Phobos by MEx are noted.

- Global mineralogical, elemental and topographical / morphological mapping (MEx will do this for Phobos with HRSC and OMEGA, although only weakly for elemental composition)
- Characterisation of the internal structure: is it a collisional fragment (and if so fractured or monolithic?) or a gravitational agglomerate? What is the balance between microporosity and macroporosity? (MEx will do this for Phobos but only via the MARSIS experiment, which is optimised for Mars not Phobos)
- Measurement of secular changes in the orbital parameters and the libration about the tidally-locked position
- Characterisation of the interactions between the moons and the martian environment (e.g. dust, gas, plasma) (ASPERA-3 on MEx will partially address this for Phobos)
- Measurement of magnetic properties
- Measurement of other key physical properties, e.g. mass / gravity field, volume, thermal inertia, microscopic structure and mechanical properties of the regolith (MEx should improve mass and volume measurements for Phobos)
- Measurement of key geochemical indicators, e.g. isotopic composition
- Measure key features relating to the possibility of sub-surface volatiles, e.g. gas emission, hydrated minerals, γ ray and neutron spectrometry, penetrating radar, permittivity (MEx will partially address this for Phobos by means of MARSIS, OMEGA and ASPERA-3).

These measurements are made by a combination of orbital / remote sensing techniques and landed, surface instruments. Consequently, the M-PADS mission design requires both aspects.

3 Spacecraft and Launch

The M-PADS mission would use a pair of identical mini-satellite-class spacecraft. These are conceived as each being capable of delivering a ~60 kg payload into a low orbit around Mars. One spacecraft would carry the orbital payload and the other a lander (Figures 1-6). Given the similarity in masses of either element, the emphasis has been to keep the design of both spacecraft the same as far as possible. The spacecraft (each ~320-360 kg) can exploit low-cost secondary payload launch opportunities into GTO or affordable small, dedicated launches into a Direct Earth Escape (DEE) trajectory. The design is such that multiple vehicles can be stacked one on top of the other. After launch, the spacecraft would separate and each use solar electric propulsion for transfer to Mars.



Figure 1. On-orbit configuration of the M-PADS orbiter spacecraft, showing its high-gain antenna.

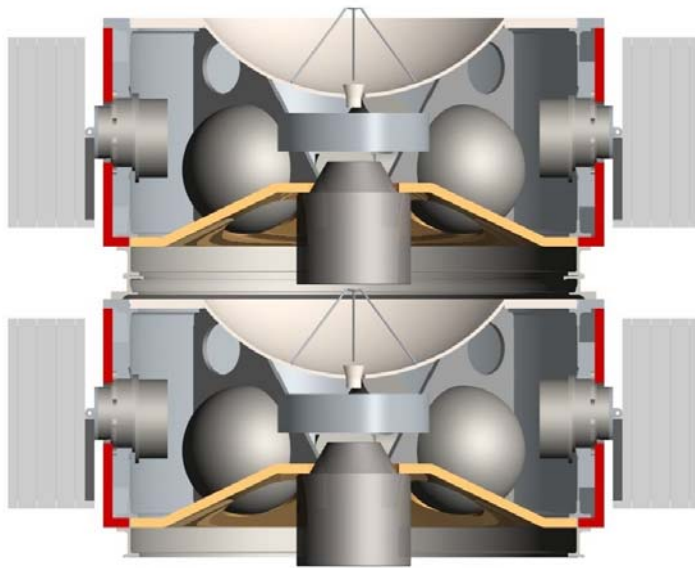


Figure 2. Cross-section of the two M-PADS spacecraft stacked for launch. Each spacecraft is a flat, irregular octagonal shape. The primary structure, separation rings, ion engine, thermal baffle, propellant tanks and high gain antenna are visible, with solar arrays shown stowed against two opposing flat sides.

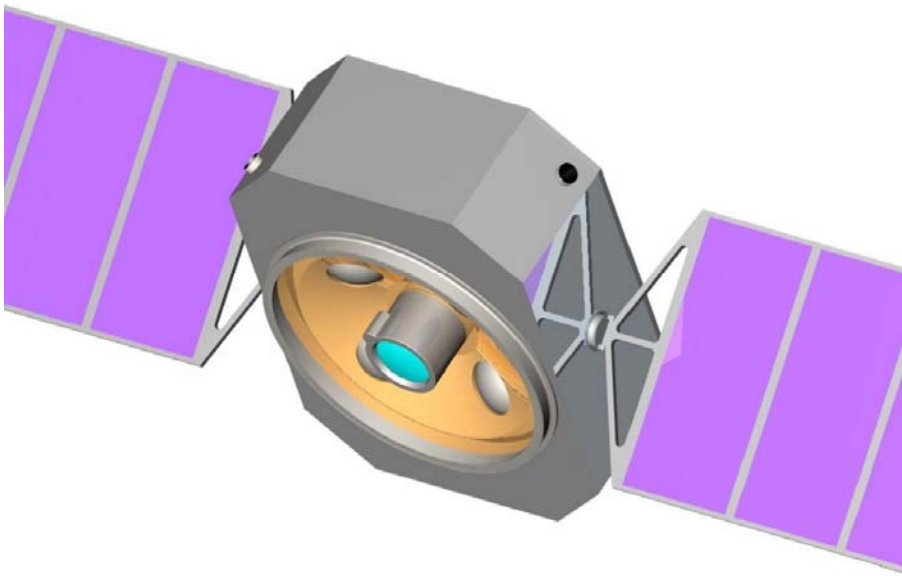


Figure 3. View of the underside of the M-PADS orbiter spacecraft, showing the single, xenon-propelled T6 ion engine and thermal baffle

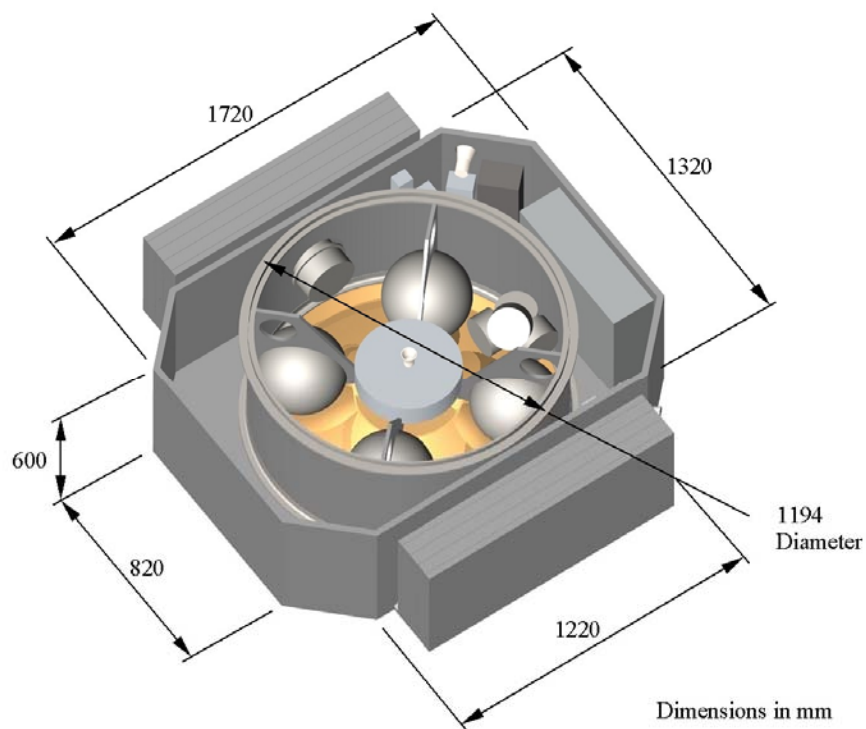


Figure 4. Internal view of the M-PADS orbiter spacecraft, showing the payload compartment and dimensions

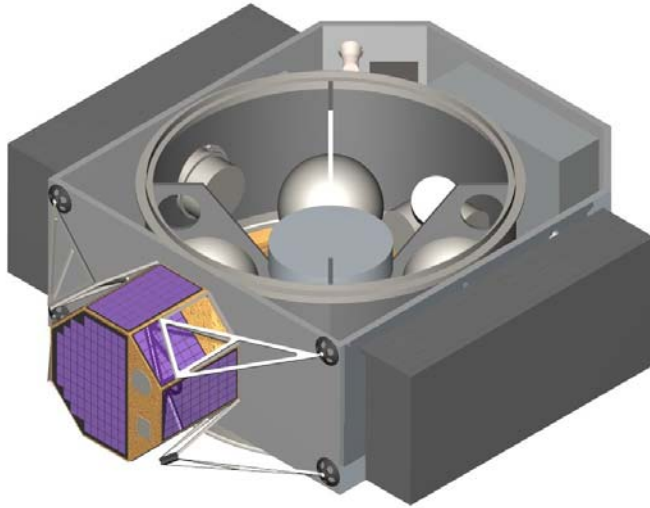


Figure 5. View of the M-PADS lander carrier spacecraft showing the internal layout and stowed lander

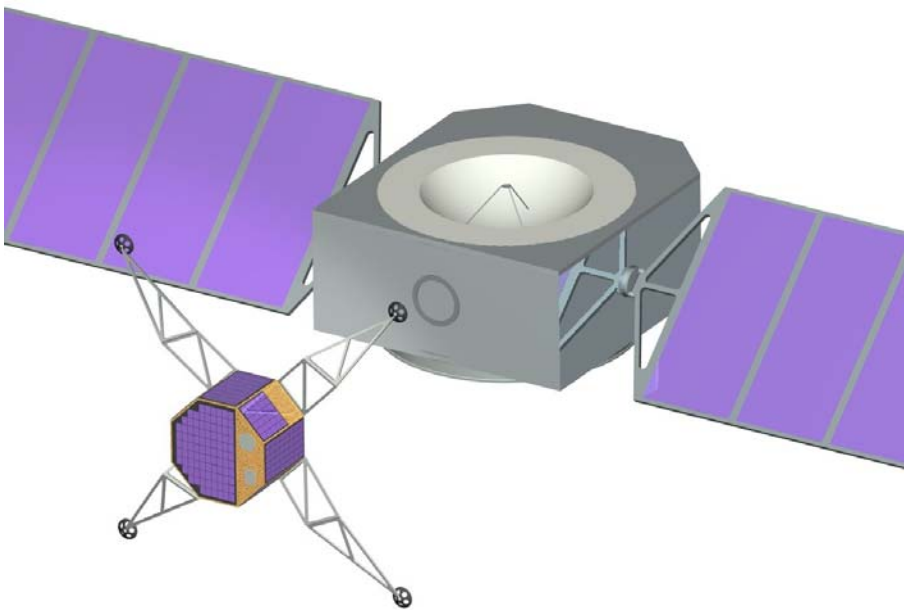


Figure 6. View of the M-PADS lander carrier and released lander

Launch options include Ariane 5 secondary payload into GTO, and Dnepr + ADU into a direct Earth escape trajectory. The spacecraft would then separate for the journey to Mars. The cost of each launch option is believed to be roughly comparable, however Dnepr offers higher payload mass, larger payload volume, lower radiation exposure, shorter flight and burn time duration. Dnepr is thus the launcher of choice, subject to the availability of the ADU upper stage. This option results in a total launch mass of 682 kg.

4 Scientific Payload and Operations

The current reference payloads and their mass budgets for the orbiter and lander are shown in Table 2. The actual payload would be selected competitively following an announcement of opportunity. Figure 9 shows how the measurement objectives of M-PADS relate to the payloads of both the orbiter and lander.

Table 2. Reference payload mass estimates for M-PADS orbiter and lander, including margins.

Orbiter payload instrument	Mass [kg]	Lander payload instrument	Mass [kg]
Core			
Multispectral Imaging System	2.4	Radio Science Investigation	0*
Radio Science Investigation	0*	Panoramic Camera	1.6
X-ray Spectrometer & X-ray Solar Monitor	5.0	Descent Camera	1.5
Near-IR Spectrometer	3.2	Sun Sensor	0.1
Laser Altimeter	2.5	α -X-ray Spectrometer	1.4
Radar Tomographer	19.4	γ ray Spectrometer	1.9
High priority			
Magnetometer	1.2	Sampling & Evolved Gas Analyser	7.5
Plasma Package	14.6	Mössbauer Spectrometer	0.4
Dust Sensor	2.0	Microscope	0.3
		In situ Physical Properties Measurements	1.2
Optional			
Thermal IR Spectral Radiometer	2.4		
Neutron Spectrometer	7.5	Magnetometer [†]	
Total	60.2		15.9

*Part of the communications subsystem (2-way Doppler ranging).

[†]Added subsequent to the original study, so not yet included in the spacecraft design exercise

Following Mars orbit insertion, the orbiter would spiral down to and rendezvous with Deimos to perform a full set of measurements and observations for several months (Figure 7). It would then spiral down to rendezvous with Phobos and perform a similar set of measurements and observations (Figure 8). Following its own Mars orbit insertion, the lander carrier would then spiral down to circularise its orbit and deliver the lander to a selected landing site on either moon. The question of which moon to target with the lander remains open; the choice would be made based upon a trade-off of scientific and technical issues. This decision could even be made after launch, based on results from the orbiter.

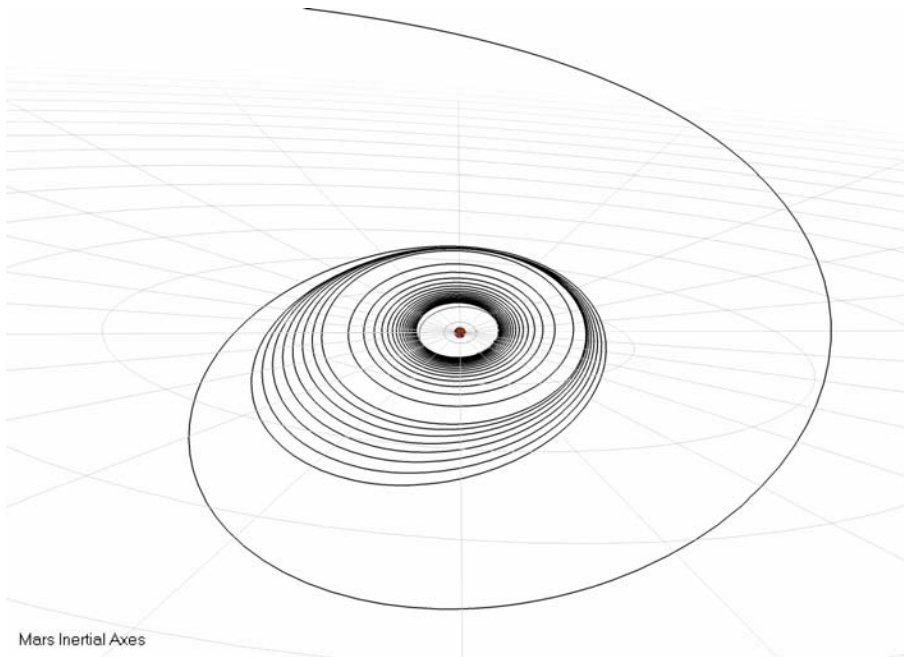


Figure 7. Trajectory of an M-PADS spacecraft Mars orbit insertion, orbit circularisation and spiral down to the orbit of Deimos (viewed from the South)

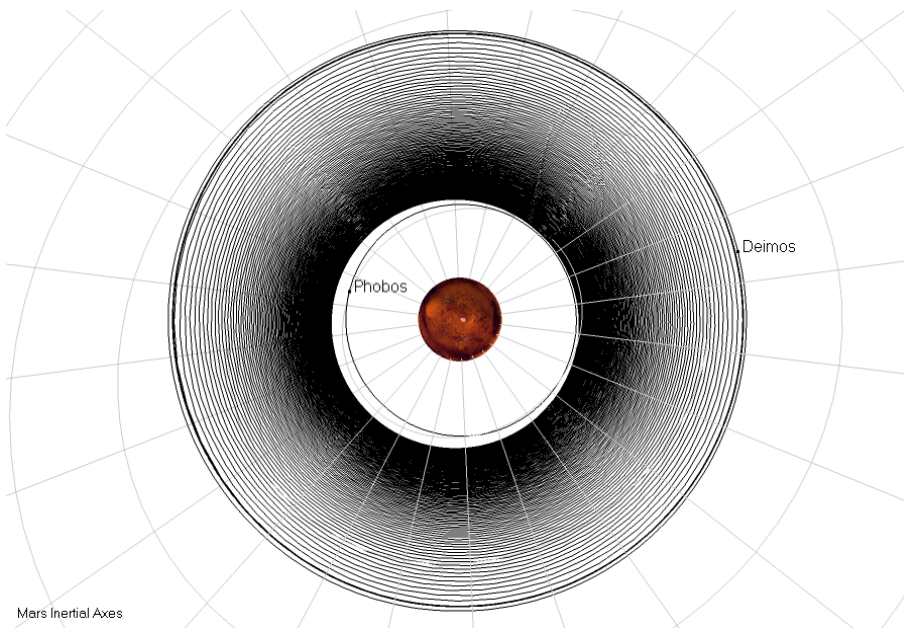


Figure 8. Trajectory of an M-PADS spacecraft as it spirals down from the orbit of Deimos to that of Phobos

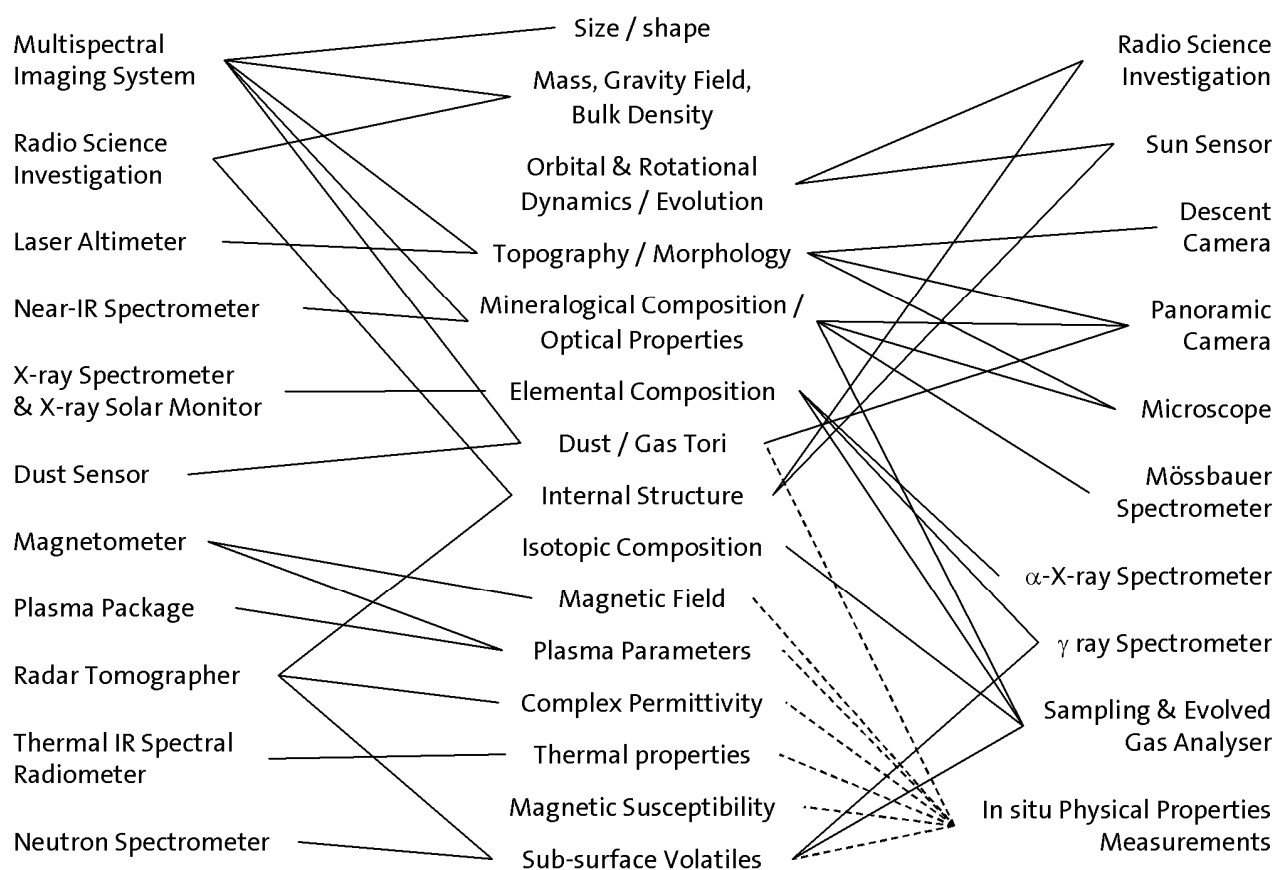


Figure 9. Linkage between the M-PADS measurement objectives (centre) with the orbital payload (left) and lander payload (right)

5 Conclusion

A viable Mars Micro Mission concept was developed in 2003 on the basis of the stated and anticipated ESA requirements for the mission, consideration of the key science questions and issues surrounding the martian moons, and consideration of the past, current and future approved and funded missions. The mission concept was formulated around a low-cost ion-propelled platform, and the launch selection and mission design analysed, together with initial considerations concerning the required spacecraft subsystems and resources available for the payloads. Payload instruments were identified to address the scientific and measurement objectives, and were largely based upon existing developments. A preliminary analysis demonstrated that the payloads and support systems could be accommodated within the platform design. Further development of the M-PADS mission concept would allow more detailed validation to be undertaken and a more detailed design to be achieved for the spacecraft, payloads and trajectories. It is also expected that the nature of suitable mission opportunities will evolve as European and international programmes are further defined.

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